

Supporting Information

Carbon Nanotube Film-Based Radio-Frequency Transistors with Maximum Oscillation Frequency above 100 GHz

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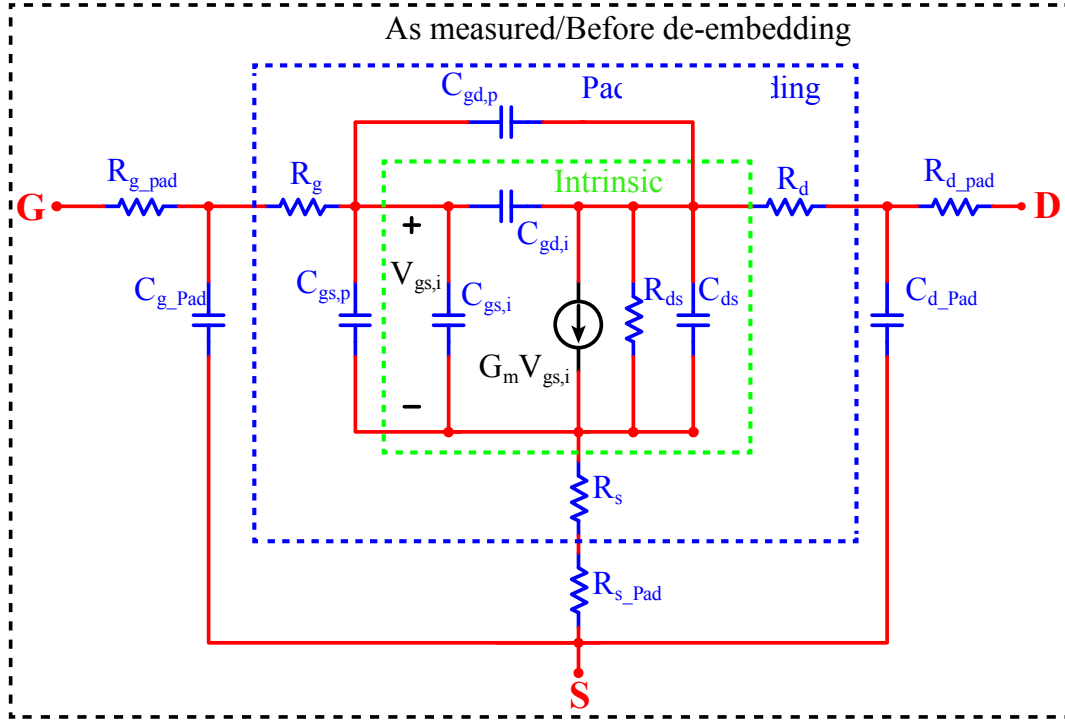


Figure S1 AC small-signal equivalent circuit model for CNT RF transistor with GSG pads. In the green box, $C_{gs,i}$, $C_{gd,i}$, C_{ds} , G_m , $V_{gs,i}$, and R_{ds} represent intrinsic gate-to-source capacitance, intrinsic gate-to-drain capacitance, drain-to-source capacitance, transconductance, the voltage on $C_{gs,i}$ divided from gate-to-source voltage and drain-to-source output differential resistance, respectively. In the blue box, $C_{gs,p}$, $C_{gd,p}$, R_s , R_d and R_g represent parasitic gate-to-source capacitance, parasitic gate-to-drain capacitance, source serial resistance, drain serial resistance and gate resistance, respectively. In the black box, C_{g_pad} , C_{d_pad} , R_{g_pad} , R_{d_pad} and R_{s_pad} represent pad parasitic resistance and capacitance.

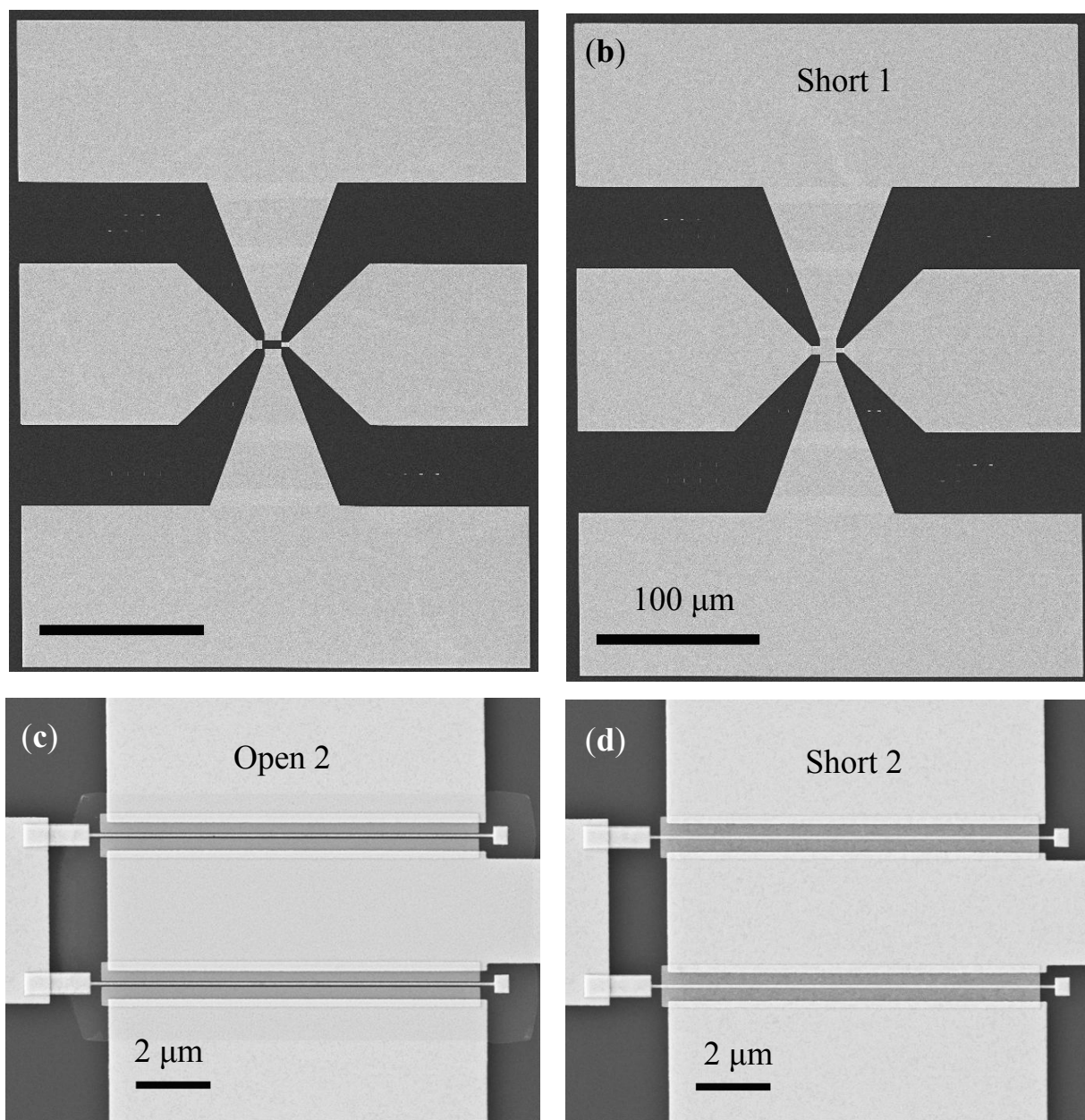


Figure S2 Structures of ‘Open’ and ‘Short’ for de-embedding. (a) Short 1 structure and (b) Open 1 structure are used to extract pad de-embedding parameters. Open 1/Short 1 structures were fabricated through using a blank square area/ a metal-deposited square area to replace the transistor region shown in Fig. 1(d). (c) Short 2 structure and (d) Open 2 structure are used to intrinsic parameters, respectively. Open 2 structure was fabricated through etching the CNT films in the channels. Short 2 structure was fabricated through shorting the source and drain. CNT films in all structures were etched.

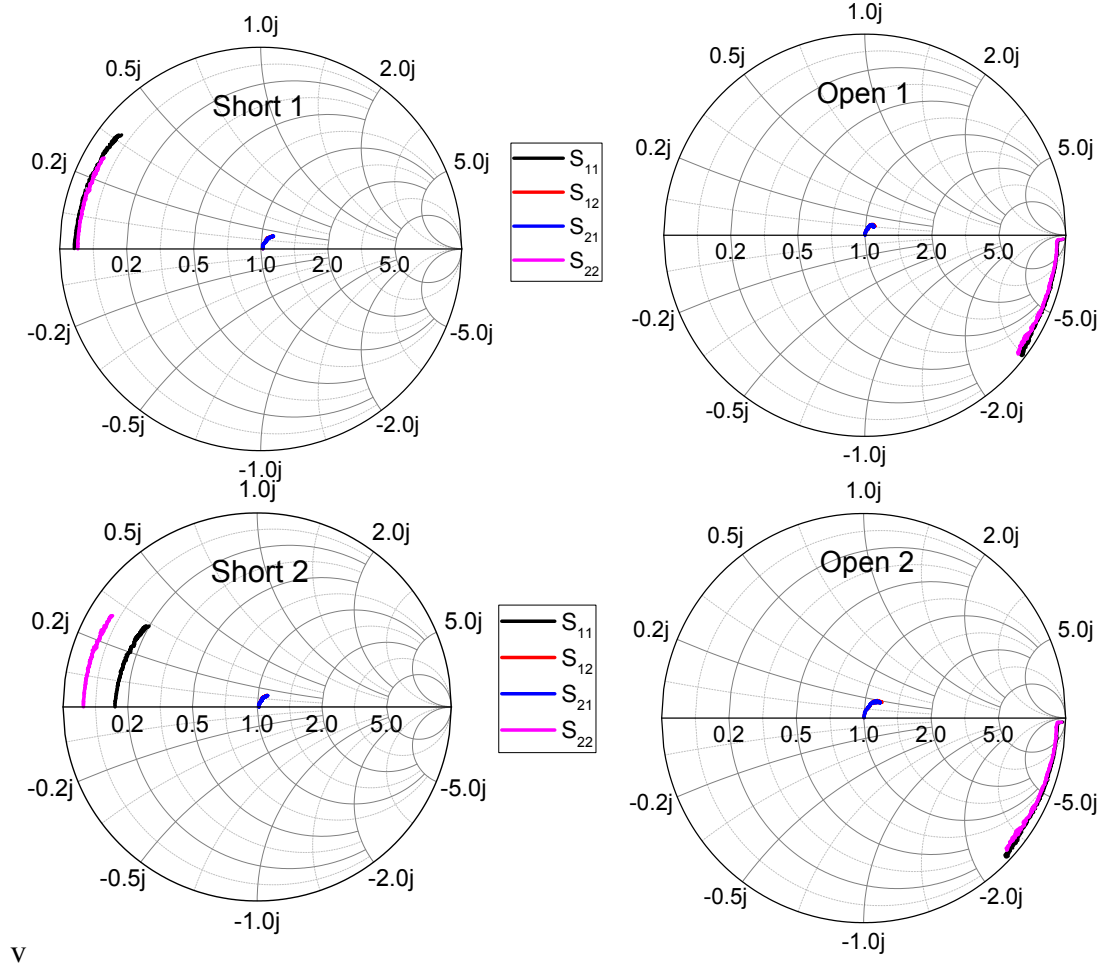


Figure S3 S-parameters of ‘Open’ and ‘Short’ structures. All biases were set to zero, and scanning frequencies were from 100 MHz to 40 GHz with a linear step of 100 MHz.

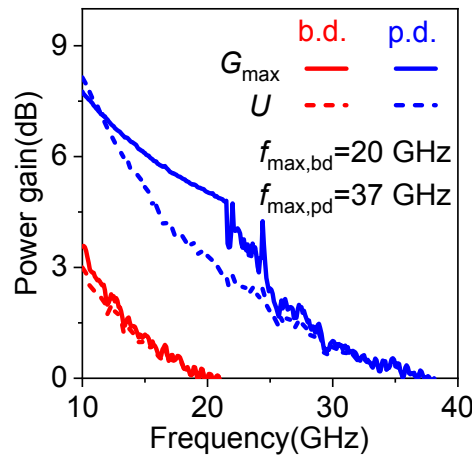


Figure S4 The f_{\max} extraction from U gain. The extracted f_{\max} from U - f relation are equal to that from The G_{\max} - f relation. The gate length of CNT RF transistor is 120 nm. V_{ds} and V_{gs} are -1.3 V and -1.5 V, respectively.

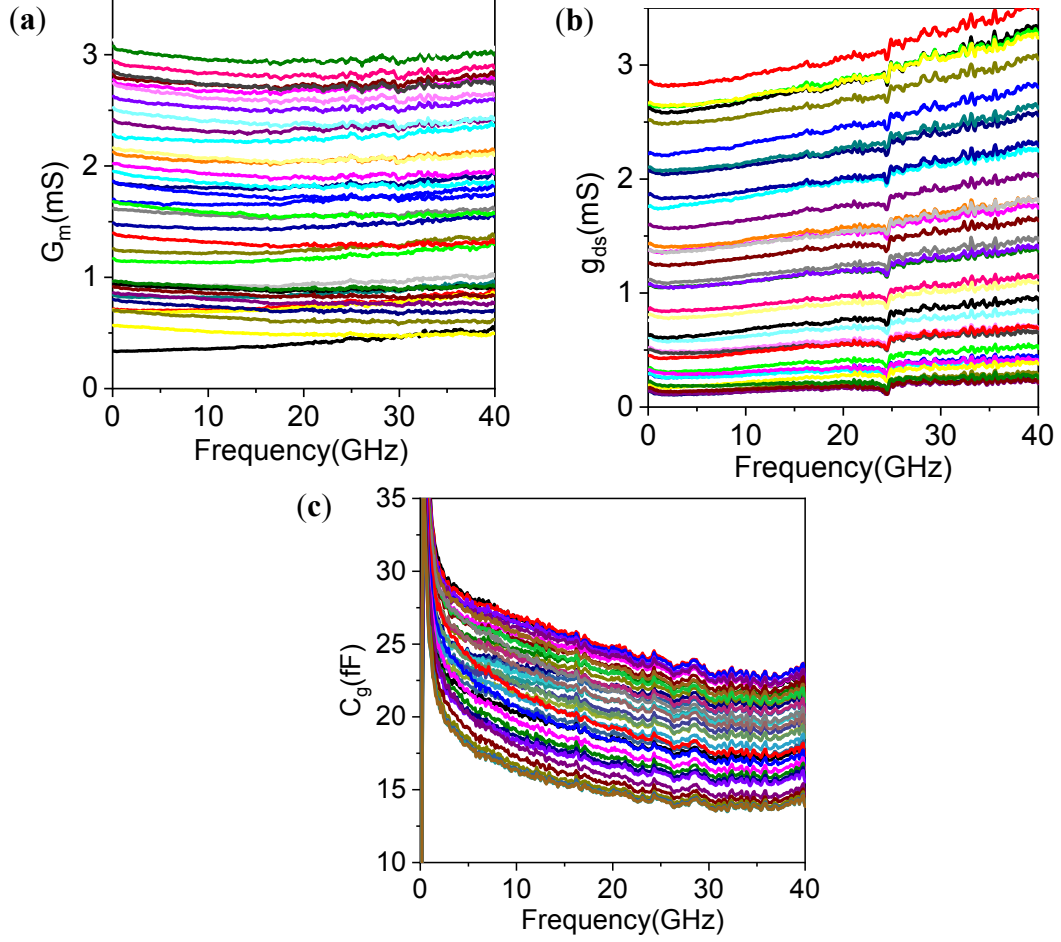


Figure S5 The extraction of device parameters (G_m , G_{ds} and C_g) from admittance parameters for RF transistor shown in Fig.2. (a) The relation of G_m with frequency. (b) The relation of G_{ds} with frequency. (c) The relation of C_g with frequency. V_{ds} is changed from -0.5 V to -1.5 V with of a step of -0.2 V, and V_{gs} is changed from -1.0 V to -2.2 V with of a step of -0.24 V. C_g is the sum of $C_{gs,i}$, $C_{gs,p}$, $C_{gd,i}$ and $C_{gd,p}$. The G_m , G_{ds} and C_g were calculated according to equations (S1-S4).

$$Y_{11}' = j\omega(C_{gs} + C_{gd}) \quad (S1)$$

$$Y_{12}' = -j\omega C_{gd} \quad (S2)$$

$$Y_{21}' = G_m - j\omega C_{gd} \quad (S3)$$

$$Y_{22}' = G_{ds} + j\omega(C_{ds} + C_{gd}) \quad (S4)$$

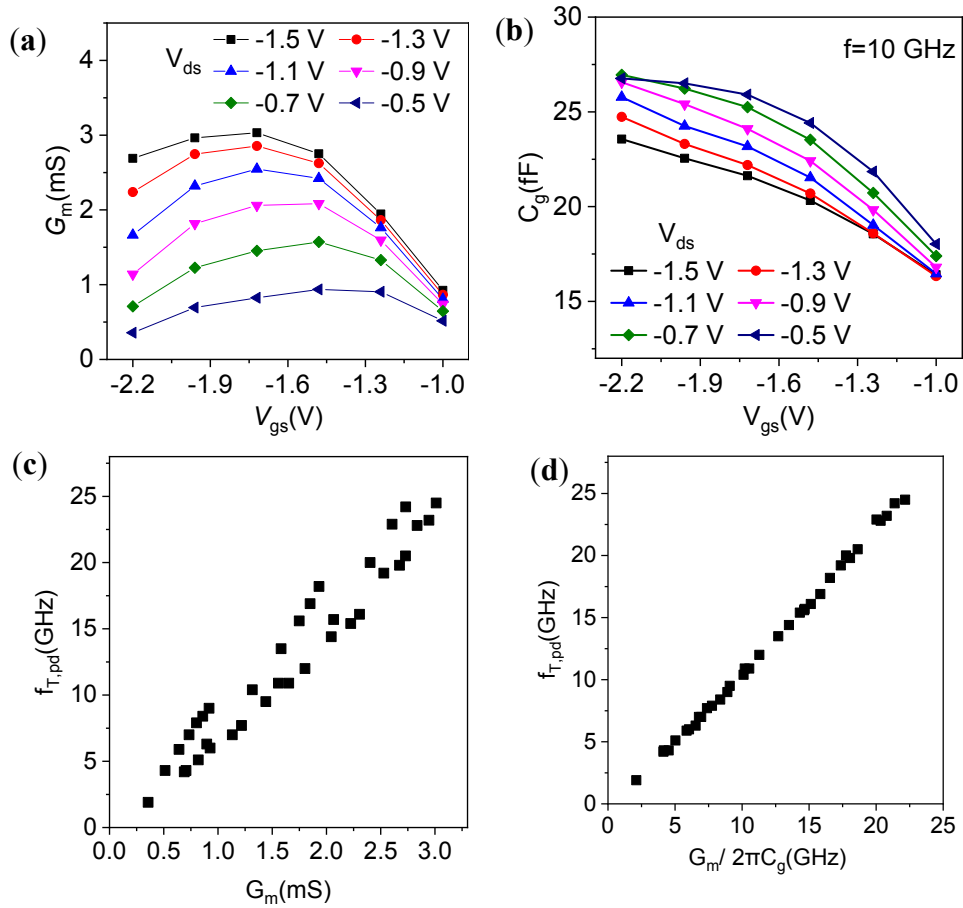


Figure S6 The relation of $f_{T,pd}$, G_m , C_g with V_{gs} and V_{gs} for RF transistor shown in Fig.2. (a) The relation of G_m with V_{gs} and V_{gs} . V_{ds} is changed from -0.5 V to -1.5 V with of a step of -0.2 V, and V_{gs} is changed from -1.0 V to -2.2 V with of a step of -0.24 V. (b) The relation of C_g with V_{gs} and V_{gs} . C_g is the sum of $C_{gs,i}$, $C_{gs,p}$, $C_{gd,i}$ and $C_{gd,p}$. (c) The relation of $f_{T,pd}$ with G_m . (d) The relation of $f_{T,pd}$ with $G_m/2\pi C_g$.

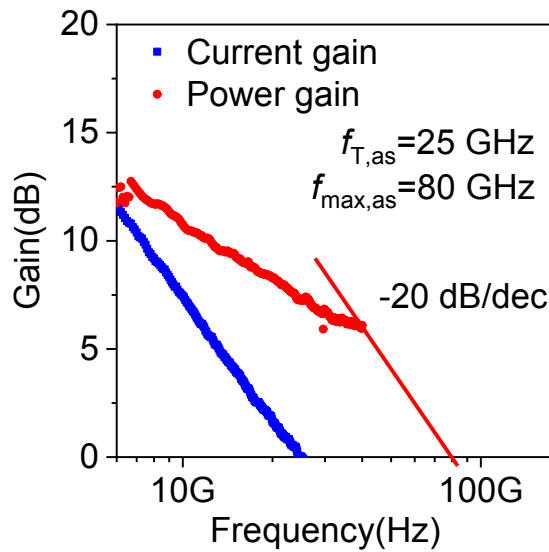


Figure S7 As-measured RF performance of 90 nm- L_g CNT transistor. V_{ds} and V_{ds} are -1.3 V and

-1.6 V, respectively. The extracted $f_{T,as}$ and $f_{max,as}$ are 25 GHz and 80 GHz, respectively.

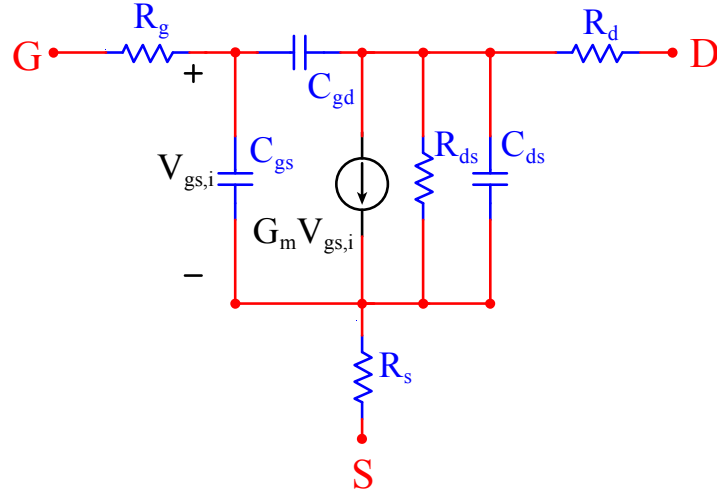


Figure S8 The simplified AC small-signal equivalent circuit model (Pad de-embedding part) for CNT RF transistor. C_{gs} is the sum of $C_{gs,i}$ and $C_{gs,p}$, and C_{gd} is the sum of $C_{gd,i}$ and $C_{gd,p}$.

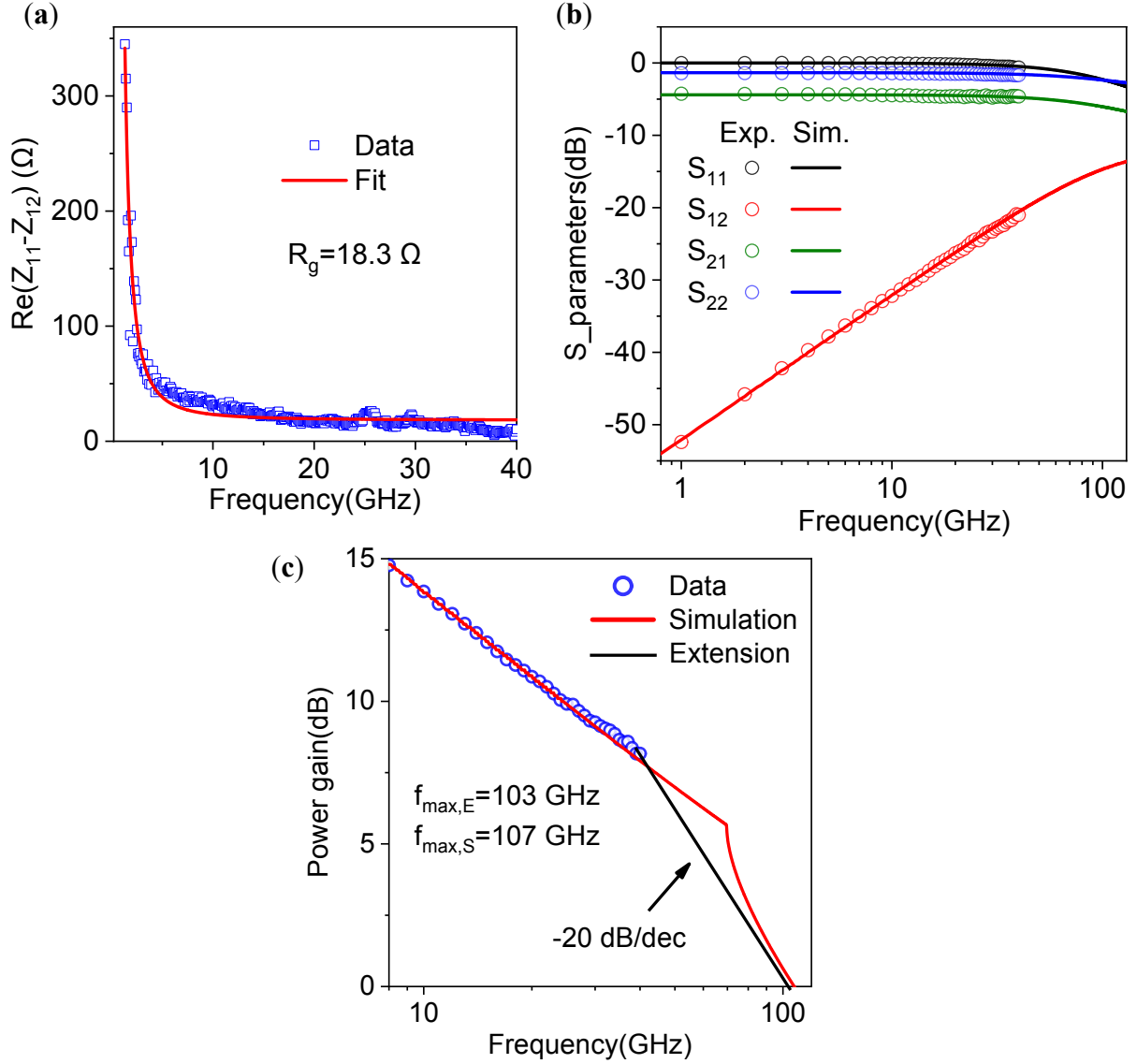


Figure S9 AC small-signal modeling and simulation of CNT RF transistor. Gate length is 90 nm, V_{ds} and V_{gs} are -1.3 V and -1.6 V, respectively. (a) The extraction of gate resistance from impedance parameters according to equation S5. (b) The simulation of scattering parameters using Advanced Design System. The equivalent circuit is shown in Fig. S7, and the parameter values of CNT RF transistor are shown in Table S2. (c) The comparison of f_{max} extracted from data extension (-20 dB/dec, black line) and simulated power gain (red line). The extension method gives f_{max} of 103 GHz, while the simulation method gives a slightly larger value of 107 GHz.

The gate resistance can be extracted from

$$\text{Re}(Z_{11} - Z_{12}) = R_g + \frac{A_g}{\omega^2 + B}, \quad (\text{S5})$$

where Z_{11} and Z_{12} are Z parameters, A_g and B are constant values at fixed bias, and ω is circular

frequency.

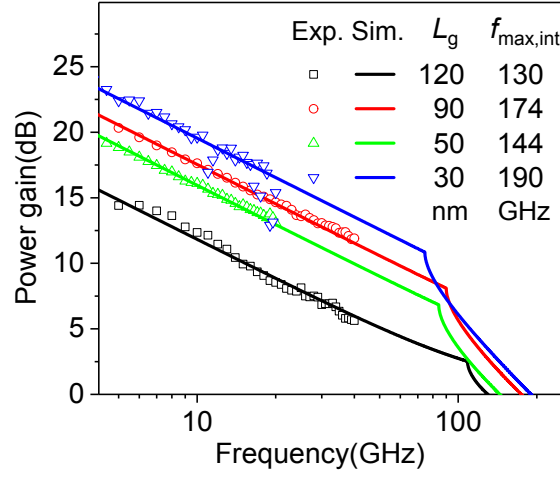


Figure S10 The intrinsic power gain versus gate length. The dots and lines represent experiment data and simulations, respectively.

Table S1 The conversions between S-parameters and Y-parameters.

S converted from Y	Y converted from S
$S_{11} = \frac{(1 - Y_{11})(1 + Y_{22}) + Y_{12}Y_{21}}{\Delta_1}$	$Y_{11} = \frac{(1 - S_{11})(1 + S_{22}) + S_{12}S_{21}}{\Delta_2}$
$S_{12} = \frac{-2Y_{12}}{\Delta_1}$	$Y_{12} = \frac{-2S_{12}}{\Delta_2}$
$S_{21} = \frac{-2Y_{21}}{\Delta_1}$	$Y_{21} = \frac{-2S_{21}}{\Delta_2}$
$S_{22} = \frac{(1 + Y_{11})(1 - Y_{22}) + Y_{12}Y_{21}}{\Delta_1}$	$Y_{22} = \frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{\Delta_2}$

Where, $\Delta_1 = (1 + Y_{11})(1 + Y_{22}) - Y_{12}Y_{21}$, $\Delta_2 = (1 + S_{11})(1 + S_{22}) - S_{12}S_{21}$.

Table S2 The device parameters for simulating CNT RF transistors.

$L_g(\text{nm})$	$R_s(\Omega)$	$R_d(\Omega)$	$R_g(\Omega)$	$C_{gs}(\text{fF})$	$C_{gd}(\text{fF})$	$C_{ds}(\text{fF})$	$G_m(\text{mS})$	$R_{ds}(\text{k}\Omega)$
120	18	24	8	9.3	7.2	1	4.2	0.94
90	15	25	18	12.3	4.2	1.5	7.5	0.57
50	10	15	41	5.6	4.8	2	6.2	0.4
30	12	19	135	2.9	3.3	2.5	4.6	0.39